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AN AIRBORNE SUNPHOTOMETER FOR USE WITH HELICOPTERS

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ABSTRACT

One solution for atmospheric correction and calibration of remotely sensed data from airborne platforms is the use of radiometrically calibrated instruments, sunphotometers and an atmospheric radiative transfer model. Sunphotometers are used to measure the direct solar irradiance at the level at which they are operatin and the data are used in the computation of atmospheric optical depth. Atmospheric optical depth is an input to atmospheric correction algorithms that convert at-sensor radiance to required surface properties such as reflectance and temperature. Airborne sun photometry has thus far seen limited use and has not been used with a helicopter platform. The hardware, software, calibration and deployment of an automatic sun-tracking sunphotometer specifically designed for use on a helicopter are described. Sample data sets taken with the system during the 1994 Boreal Ecosystem and Atmosphere Study (BOREAS) are presented. The addition of the sun photometer to the helicopter system adds another tool for monitoring the environment and makes the helicopter remote sensing system capable of collecting calibrated, atmospherically corrected data independent of the need for measurements from other systems.

1.0 THE NEED FOR AN AIRBORNE SUN PHOTOMETER

Conversion of airborne at-sensor radiance measurements to at-surface reflectance is needed for accurate inference of earth surface biophysical parameters. Prior solutions have relied upon measurements of surface reference targets of known reflectance, duplicate surface-based instruments mounted to view reference panels, and the use of radiometrically calibrated instruments and sunphotometers with atmospheric radiative transfer models (Markham et al., 1988). For some low altitude data collection under clear conditions it can be assumed that the influence of the atmosphere is negligible (Lawrence et al., 1994). However, corrections for atmospheric path length effects between the sensor and the surface can be considerable, even at low altitude, which often renders some solutions

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inappropriate.

The use of radiometrically calibrated instruments and sunphotometers is a promising solution that provides both atmospheric correction and conversion of at-sensor radiance to at-surface reflectance. Sun photometers are used to measure the direct solar irradiance at the level at which they are operating, allowing for the computation of the atmospheric optical depth. This provides an input to atmospheric models that convert at-sensor radiance to required surface properties such as reflectance and temperature. Using satellite-based systems, only the surface-based sun photometer is required as is currently being done with a project that seeks to deploy a global array of sun photometers (Holben et al., 1994). For aircraft platforms, ideally, one sun photometer would be operated on the surface, providing optical thickness for the entire atmospheric column and another would be operated at the altitude of the platform, providing optical thickness from the platform to the top of the atmosphere. The difference between the full atmospheric column optical thickness and the optical thickness from the platform to the top of the atmosphere yields optical thickness between the platform and the surface, which is a desirable quantity for atmospheric corrections.

An automatic sun tracking photometer for helicopters (ASTPH), was designed and built taking into account the special environmental conditions of helicopters (Figure 1). The ASTPH is the latest of a series of modifications to a helicopter-based optical remote sensing system developed since 1984 by researchers at NASA Goddard Space Flight Center (GSFC) and Wallops Flight Facility (WFF) (Williams et al., 1984; Walthall et al., 1996). Comparisons between data sets collected during the First International Satellite Land Surface Climatology Project (ISLSCP) Field Experiment (FIFE) campaigns indicated atmospheric influences, even at low altitude (Deering et al., 1992). Design, development and fabrication of the ASTPH took place in the year prior to the field deployment for the BOReal Ecosystem Atmosphere Study (BOREAS) in Canada (Sellers et al., 1995). Several modifications have been made since the initial design.

Although the primary motivation for development of the helicopter automatic sun tracking photometer is providing data for calibration and correction of remotely sensed measurements, the system is useful for the acquisition of measurements in support of atmospheric research. Optical thickness as a function of height in the boundary layer, which an airborne sunphotometer easily provides, is needed to better understand vertical aerosol distributions.

2.0 DESIGN CRITERIA

Design specifications for the instrument included a) the ability of the system to withstand the significant amounts of vibration characteristic of helicopters and to provide reliable readings while looking through the arc of the rotating main rotor blades, b) a modular design for future additions or modifications, c) the use of off-the-shelf components where possible to keep cost low, d) compatibility with other sun photometers (spectral bands and calibration), e) the use of PC-based data logging, and f) minimal alterations to the airframe. The size of the system, available space, cabling considerations and safety also played a role. Engineers, pilots and mechanics experienced with helicopters were consulted during the design phase and played an integral part in integrating the system onto the aircraft. A Bell** UH-1H "Huey" helicopter operated by NASA Wallops Flight Facility (WFF) served as the platform.

3.0 INSTRUMENT DESCRIPTION

The ASTPH consists of an optical head containing locations for 10 sensors located around a quad-detector on a pointable mount (Figure 2). The quad-detector is used to track the sun and has a 30 degree field of view (FOV). The tracking circuitry reads the four detectors and repositions the azimuth and zenith angle motors until the detector outputs are equal. A PC system interfaced via a GPIB bus is used to calculate angles and position the mount to view the solar disk on command from the operator, which starts the tracking sequence. Once the tracking system has engaged the data collection process begins.

**Manufacturer names are given for information purposes and do not imply endorsement by USDA or NASA.

The optical head is held by a UNIDEX-11 motion controller (zenith and azimuth axes), built by Aerotek, Inc.. The controller has an onboard CPU system, front panel display, and GPIB port interface. The entire mount is attached to the aircraft on the starboard side, directly overhead of the operator. Data and control cables are fed through an air vent into the back of the experiment instrument rack. The usable azimuth range of the ASTPH is approximately 12:00 to 7:00 with 12:00 being the direction of the nose of the aircraft. The zone of azimuthal occlusion is created by the cable length and helicopter main rotor mast. This necessitates that the helicopter be oriented such that the port side of the helicopter faces away from the direction of the sun.

The photometer sensors in use at the present time are silicon detectors with 2 degree FOV optics. Temperature effects on the detectors are dealt with via a temperature control circuit that keeps the detectors at the temperature used during calibration. Seven spectral channels (440, 540, 613, 670, 870 and 1030 nm) were chosen to span the visible and near infrared (NIR) wavelengths such that except for the 940 nm channel, gaseous absorption is either absent or minimal. The 940 nm channel measures the water column abundance above the helicopter. Many of these channels coincide in wavelength with the CE-318 Cimel instruments currently deployed in support of major global satellite image analysis programs (Holben et al., 1994). The physical configuration of the helicopter sunphotometer provides space for three additional spectral channels for future use, probably beyond 1000 nm where extinction from larger particles is sought.

Sampling rate considerations were a key issues in the design of the instrument. A major problem of mounting a sun photometer on a helicopter is that the system must acquire data and stay locked on the solar disk while viewing between the moving rotor blades. Reduction of irradiance beneath moving rotor blades can be considerable. A sampling rate programmable up to 333ks/sec can be obtained, but was not necessary (Figure 3) with the rotor blade frequency of 9Hz for a complete rotation (18 Hz for blade-to-blade rotation).

4.0 DATA ACQUISITION SYSTEM DESCRIPTION

Analog voltages from the seven photo-detectors located in the optical head are digitized by a National Instruments DAQ #AT-MIO-64E-3 12-bit analog to digital converter. The DAQ card is located in one of the ISA slots of an industrial PC-486 rack mounted computer inside the helicopter cabin. This state of the art A/D card was needed to get the proper sample rate and collect data from other sensors on board the helicopter (e.g., an atmospheric pressure transducer, altitude data encoded from a RADAR altimeter, a Photosynthetically Active Radiation (PAR) sensor, a pyranometer, two infrared thermometers (IRTs), an eight band Modular Multiband Radiometer and a temperature control device for a spectroradiometer system).

The software used for data collection, data handling and real-time display was National Instruments LabView for Windows. This commercially available software allows the user to set up a software system configured to the specific hardware in use without having to generate low-level computer language code. The compiled stand alone program for the application here is approximately 1 megabyte in size. This program is a multi-tasking, real-time software application that while not actually multi-tasking via multiple processors, does have each individual task sharing time on the same central CPU. The software application for the sun photometer data is also controlling and acquiring data from the other sensors also. A digital voltmeter with channel selector switch is located on the front panel which allows the operator to view the voltage coming from a single channel.

The UNIDEX-11 operates in two different modes: TRAC, and REGULAR. The REGULAR mode is used to move the mount to the desired starting position (zenith and azimuth). The TRACK mode is used when the quad detectors are commanded to take control and track the sun. The software automatically switches in and out of these modes via commands from the GPIB port.

The data collection process begins by moving the mount from the HOME (azimuth angle = 12:00, zenith angle = 0 degrees) to the desired zenith and azimuth angles as specified from operator input. This initial input must be within 30 degrees of the solar disk. The PC-486 then switches the UNIDEX-11 into the TRACK mode and the quad-detectors take control, "locking on" the solar disk. The analog output of the photo detectors is sampled for 100 ms and usually contains at least one blade passing in the data stream. The data is acquired from the hardware at a rate of 5 ms (which yields 20 data points), and then all data is plotted on the operator screen. The digitized raw solar irradiance data are saved to disk along with barometric pressure and altitude data which are used later in the data processing sequence.

5.0 CALIBRATION AND DATA PROCESSING

Calibration of a sunphotometer involves determining the exoatmospheric voltage response in each of the channels. Langley and intercomparison methods are employed that use the Bouguer law of atmospheric extinction for those channels that do not include gaseous discrete absorption. Calibration of the 940 nm water absorption channels are not reported here. Extinction due to Rayleigh scattering and absorption due to ozone in the Chappuis band are included in the calibration procedure.

The raw data were first screened for voltage dropouts caused by the passage of a rotor blade. The resulting "clear" data was then processed to obtain aerosol optical thickness. Calibration was performed by two methods. In April 1994, the sunphotometer was taken to Mount Lemmon (9167') to perform a Langley calibration (Halthore et al., 1992) in the non-water absorption channels. Since the instrument wiring was reconfigured after the calibration, it was felt that the Mount Lemmon calibration may not be valid for flights in the BOREAS Intensive Field Campaigns (IFCs). Thus, a special effort was made to perform calibration by intercomparison with sunphotometers that were thought to be better calibrated.

During the May 1994 IFC-1, intercomparison was made with the NASA Ames sunphotometer at Candle Lake (Wrigley, R., private communication). The resulting calibration coefficients differed from Mount Lemmon calibrations by at most 3% and typically 2% (Table 1) in most channels, thus showing that the instrument response had not been drastically altered by the reconfiguration. However, it was decided to use the Ames intercomparison coefficients for both IFCs I and II.

Due to problems with data logging during the September 1994 IFC III, the signals from 3 channels were lost (channels 2, 5 and 6). Calibration once again became a problem of utmost concern. Intercomparison with an 8 channel sunphotometer, commonly called SXM-2, was done at the BOREAS Operations site near Candle Lake on a clear day (September 16). In the absence of a mountain site calibration, the NASA-built SXM-2 sunphotometer, with detector temperature control and automatic operation including data logging, was itself calibrated by comparison with a "standard" Cimel sunphotometer at Goddard Space Flight Center in October, after the IFC. The transferred calibration (TABLE 1) shows deviations of less than 3% in all functioning channels. It was decided to use this calibration for analyzing data from IFC III.

The fact that different calibration methods yield calibration coefficients to within about ± 3% determines the uncertainty in the measured aerosol optical thickness to about ± 0.03; the actual uncertainty is probably a little higher than this due to variability in the data. Considering the conditions under which the helicopter sunphotometer operated, this level of uncertainty is acceptable.

6.0 SAMPLE DATA SETS

Figure 4 shows aerosol optical thickness in the 4 channels that were operating during IFC III for a clear day (September 16, 1994). Also plotted is the result of measurements from the SXM-2, a sunphotometer that was used as a standard for intercomparison. The agreement between the two instruments is therefore not surprising. The reason for the apparent disagreement at, for example, the 1030 channel between the two instruments is due to variability in the helicopter sunphotometer data. The variability is seen in all channels even after removing the data dropouts due to passage of the rotor blade and is of the order of ± 0.1 in the derived aerosol optical thickness although much of it is confined to within about ± 0.03 (Figure 4). This variability is a direct consequence of variations in the voltage, the cause for which we can only speculate to be either (a)shadows and reflection due to rotor blades; (b)pointing inaccuracies; (c)stray light noise in the collimators due to variability in pointing; (d)other vibration related noise.

Figure 4 also shows that data are obtained rapidly at least every second simultaneously in all channels for a short duration at each site. The mean and median values of derived aerosol optical thickness are close to each other for the data shown but the former is much larger if ALL the data are taken into account (that is including those data that clearly show the effects of partial covering by the rotor blades). It must be noted that the helicopter was just above the ground at the BOREAS Operations Center with blades rotating for the data shown in Figure 4.

In Figure 5 a comparison between a ground based sunphotometer and the helicopter sunphotometer flying 1000 feet above the surface is shown. The surface measurements were made by an 7 channel completely automatic instrument commonly known as a Cimel sunphotometer which was itself calibrated to a reference instrument at

Goddard. Only two representative values for the helicopter sunphotometer are shown in this flight over a BOREAS Site (Young Jack Pine site in the Southern Study Area). The agreement between the two instruments is satisfactory given the known uncertainty in calibration of the two instruments and the variability of the helicopter sunphotometer. A similar analysis for September 6, 1994 at the same site showed deviations of the order of 0.04 to 0.06 in the three overlapping channels between the mean (and median) values of the helicopter sunphotometer and the Cimel sunphotometer. Curiously, the values measured by the helicopter sunphotometer were higher thus raising questions as to the magnitude of the uncertainty in the calibration of either one or both the instruments.

7.0 CONCLUSIONS

Successful use of a sunphotometer aboard a helicopter is demonstrated. Due to the rapid response time of the silicon detector and the associated electronics, the passage of the rotor blade is a mere nuisance that can be removed during data analysis. Reasonably accurate values of the aerosol optical thickness are obtained in all the channels. Variability in the measured voltages translates directly to variability in derived aerosol optical thicknesses.

The addition of an on-board automatic sun-tracking sunphotometer system has made the helicopter optical remote sensing system a self-contained mobile unit that can be used to acquire calibrated remote measurements of surface parameters. Initial experience with this system shows that accurate and reliable measurements of surface irradiance, surface reflectance and temperature can be made in remote areas where surface access is difficult or impractical.

8.0 ACKNOWLEDGEMENTS

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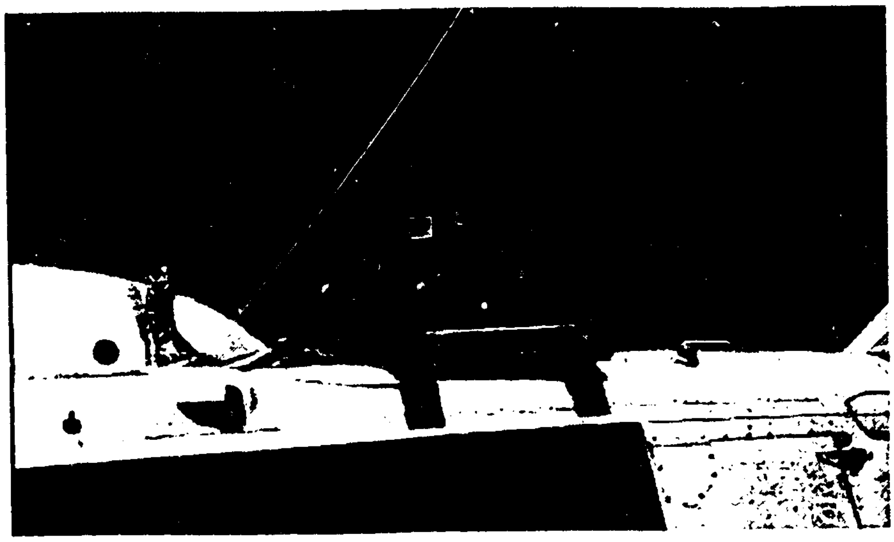

Figure 1. Automatic Sun Tracking Photometer for Helicopters (ASTPH) mounted on the starboard side of a NASA Bell UH-1H helicopter.

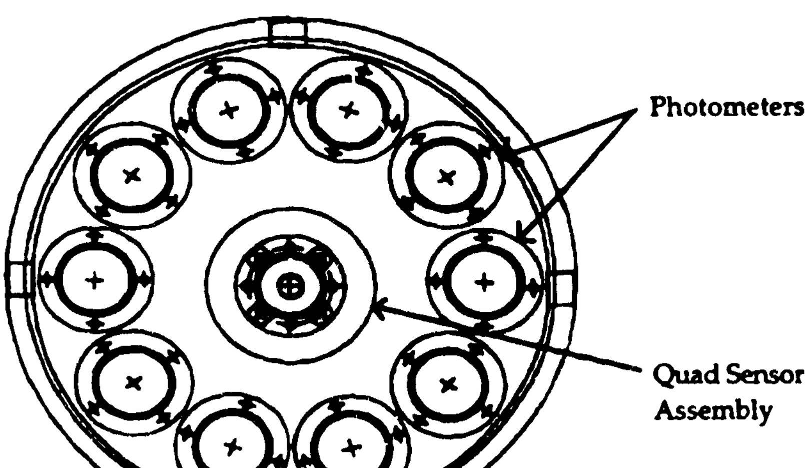

Figure 2. Diagram of the front view of the sensor head showing the arrangement of the 10 photometer detectors around the centrally located quad detector.

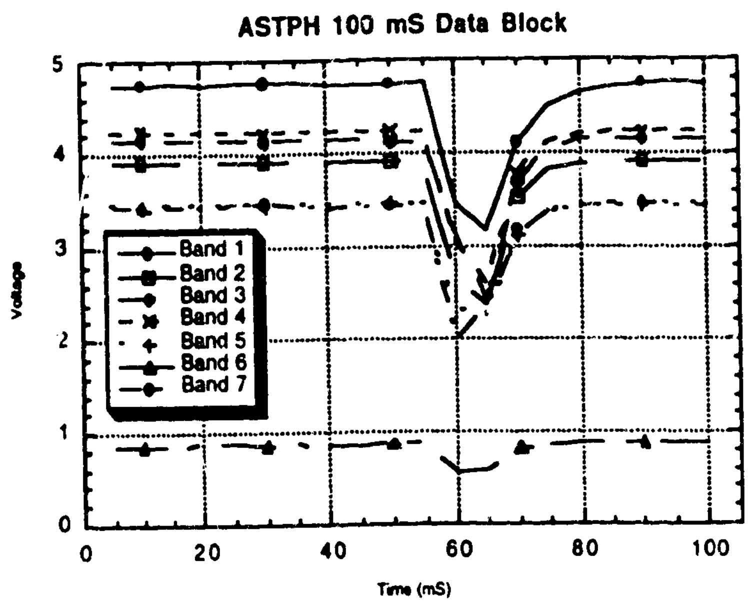

Figure 3. Sample ASTP 100 mS data block illustrating how the rapid sample time is sufficient for sampling between passes of the main rotor blades. The extremely low values for band 6 are due to an error in the optical alignment.

TABLE I: Summary of Calibration of Helicopter Sunphotometer

	Channel Number							
	1	2	3	4	5	6	7	
	Wavelength, nm							
Location	441	540	613	670	870	940	1030	Method
Mount Lemmon	8.45	5.56	5.58	5.24	4.02	-	3.69	Langley Plot
Candle Lake	8.69	5.65	5.48	5.35	4.09	-	3.75	Intercomparison with Ames.
Candle Lake	8.68	-	5.63	5.39	-	-	3.83	Intercomparison with SXM-2

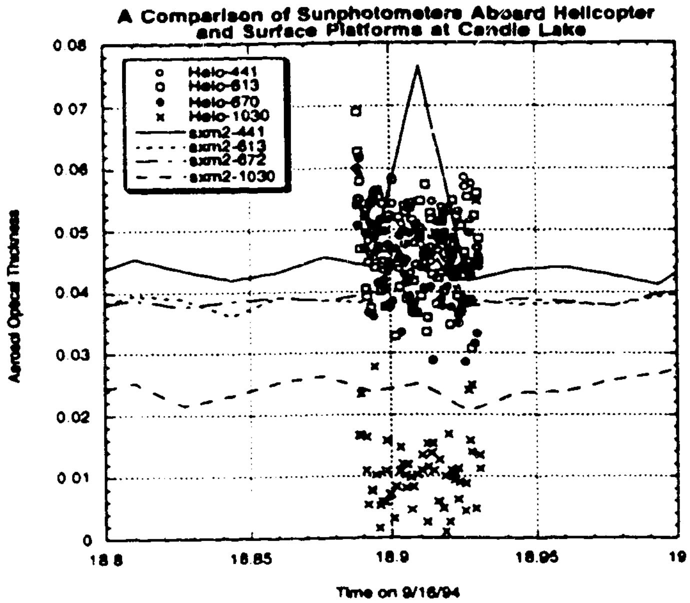

Figure 4. ASTPH measured aerosol optical thickness (AOT) compared with ground-based sun photometer-measured values. The variability of the ASTPH data is clearly apparent.

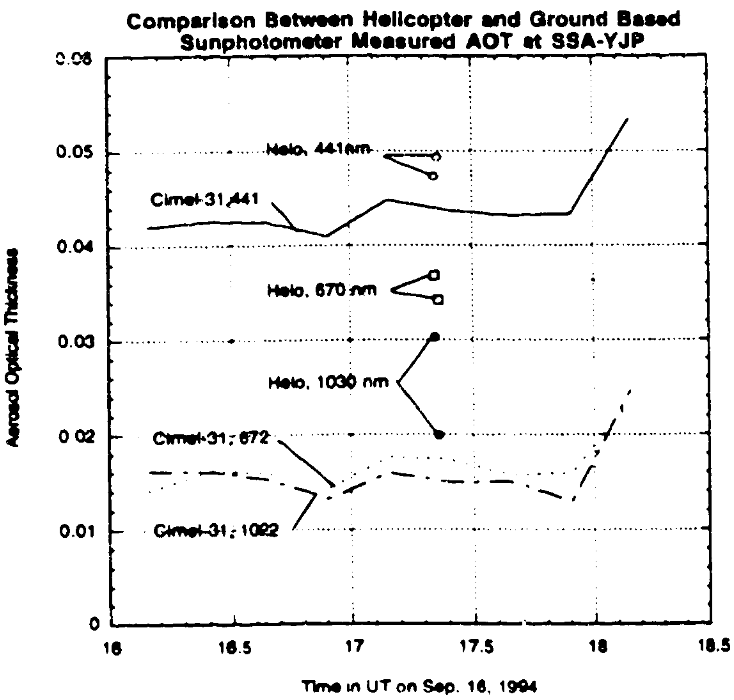

Figure 5.Comparison of ASTPH values obtained 1000 feet above ground with values from a ground-based sun photometer shows reasonable agreement for this clear day. The ASTPH values should be lower than those from the surface, thus illustrating uncertainty in absolute calibration.

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